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Life cycle CO_2 assessment of concrete by compressive strength on construction site in Korea

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ABSTRACT

As research on the reduction in the life cycle carbon dioxide ($LCCO_2$) emissions of buildings has become increasingly important, the development of technologies that can quantitatively assess the $LCCO_2$ emissions of a building at the level of the construction materials is essential. In addition, concrete of various compositions, such as high-performance concrete mixed with fly ash and blast furnace slag and eco-concrete, has become readily available and thus, a quantitative evaluation of CO_2 basic units for these new materials is needed. However, basic units for various types of concrete are not provided by the National Life Cycle Inventory Database (LCI DB) in Korea. Therefore, thorough research on these materials has become an important priority.

In this study, a method to assess $LCCO_2$ emissions using the compressive strength of concrete is proposed. Specifically, the compressive strengths of various mixes of concrete that are employed at construction sites in Korea were utilized to evaluate CO_2 emissions. Comparisons according to the characteristics of each mixture were also made.

Approximately 560 concrete mix designs used at construction sites were first classified according to the compressive strength, admixture, and season. The concrete CO_2 emissions assessment process was carried out for the concrete raw materials production stage, the concrete raw materials transportation stage, and the concrete production stage; quantitative assessment methods are proposed for the CO_2 emissions at each stage. Based on the proposed assessment methods, an evaluation of the concrete CO_2 emissions was conducted and the obtained values were analyzed.

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1. Introduction

1.1. Background and objective of the study

As a result of the most extensive convention on climate change by an international society, a 5-year (2008–2012) reduction in green house gas emissions is being implemented in accordance with the Kyoto Protocol, which was adopted at the United Nations Framework Convention on Climate Change (UNFCCC) in 1997. Based on the main agenda of the convention, the primary goals of the 15th UNFCCC Conference of the Parties (COP15), which took place in Copenhagen, Denmark, were to reduce green house gas emissions until 2020 and support reductions in developing countries. As a result, proactive responses for the prevention of global warming are in demand in both developed and developing countries [1].

In 1985, the World Meteorological Organization and the United Nations Environment Program suggested that the main cause of global warming was CO_2 emissions, which contributed 80% of the total green house gas emissions. Based on their report, energy consumption and CO_2 emissions by buildings contribute 38% of the total national CO_2 emissions in the United States. Thus, the field of construction can be considered as an eco-destructive industry and efforts to transform construction into an environmentally friendly industry are necessary for environmental conservation. In particular, concrete, the primary material used in the construction industry, emits a significant amount of CO_2 from the material (cement, aggregate, admixture) production stage to the manufacturing stage. In countries that are more environmentally conscious, studies focusing on CO_2 emission and energy-conserving concrete production are actively underway, as are studies examining the production of concrete with diverse mix designs with high contents of fly ash and blast furnace slag. While a quantitative CO_2 basic unit assessment for such a variety of concretes is necessary, the basic costs for various types of concrete are not provided by the national LCI database in Korea, and no explicit study on this topic is currently underway [2,3].

In this work, a method for assessing life-cycle CO_2 emission based on the compressive strength of concrete in Korea is proposed. The CO_2 emission is evaluated based on the compressive strength (by admixture and season) of diverse types of concrete that are actually used at construction sites in Korea. Finally, an environmentally friendly concrete production assessment system is proposed based on the relationships among the characteristics of life-cycle CO_2 emissions.

1.2. Contents and methods of study

Approximately 560 concrete mixes that are used at construction sites in Korea were classified based on compressive strength, admixture, and season. The concrete CO_2 emission assessment process was conducted for the raw material production, concrete raw material transportation, and concrete production stages. A quantitative assessment method for CO_2 emission at each stage is also proposed and the acquired estimates were analyzed by evaluating the CO_2 emission from the concrete. In addition, operators that can compute the energy consumption and CO_2 emission at each step and the content composition of the required ingredients are suggested. The calculated CO_2 emission from the concrete production processes was compared with standard concrete CO_2 emission [4,5].

2. Examination and analysis of existing literature

2.1. Current LCA techniques

Studies assessing the quantitative environmental loads of numerous industrial products are currently underway. To quantitatively assess and compare the environmental loads of different products, a basic unit is needed for common and standardized materials. In Korea, the Ministry of the Environment provides the National Life Cycle Inventory database (LCI DB), which is utilized for the life cycle assessment (LCA) of products [6].

The analysis used to establish the national LCI DB begins with the development of a flow chart. In this process, the blueprints and estimates obtained from the manufacturers of the products and systems are employed. The flow chart includes information on the energy, material consumption, and substances used throughout the life cycle of a product or a process, including the extraction, manufacturing, processing, transportation, distribution, use, and ultimate disposal of a material. Companies provide details on the flow chart of a product. These flow charts are subsequently incorporated into the LCI DB list through external verification [7,8].

For construction materials, products, and buildings, life cycle inventories (LCI), life cycle assessments (LCA), and environmental product declarations (EFD) should be conducted. An LCI database is established according to the country or region, and approximately 400 national modules have been established in Korea.

2.2. Analysis of $LCCO_2$ assessment for construction materials

An input–output analysis utilizes an input–output table to analyze the $LCCO_2$ emissions of construction materials. An input–output table may be described as a comprehensive table that displays all transaction details related to the production and disposal of goods and services occurring within a construction economy according to a certain set of principles and formats. Input–output tables can be used as the basic unit of an LCA so that the CO_2 emissions from each material can be determined. However, in the construction industry, only a small fraction of construction materials are described in the input–output table and items from the input–output table may not be directly related to current technologies and products. Furthermore, because the number of items related to construction materials is extremely insufficient with respect to the establishment of a basic unit of CO_2 emissions for new technologies or methods such as recycling, quantitative assessment is difficult.

The Environmental Industry & Technology Institute of Korea currently provides basic units of CO_2 emission for many industrial products using an input–output analysis. However, for construction products, the characteristics of diverse production processes that vary according to their purpose are not considered. Specifically, only a few representative compressive strengths are examined for concrete. Furthermore, because various conditions at the time of

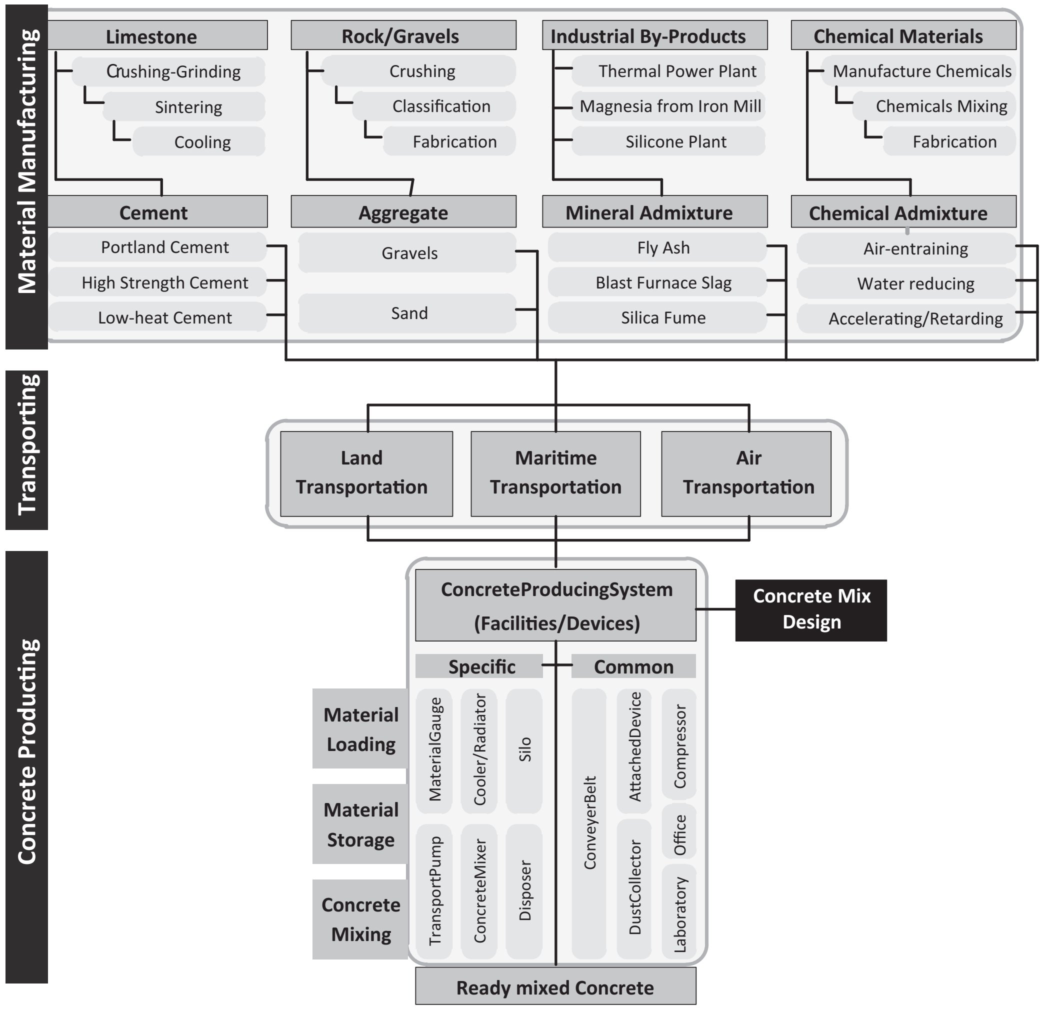

Fig. 1. Concrete production processes.

construction, such as the mix proportion of the material phase, methods of transportation used in the transportation phase, and the manufacturing equipment employed in the production phase, are not taken into consideration, eco-concrete and high-performance concrete are difficult to analyze. Therefore, a systematic method of assessing concrete products for diverse production processes must be developed [9,10].

3. Development of concrete life-cycle CO_2 emission assessment system

3.1. Overview

For the life-cycle CO_2 emission evaluation, the production processes for concrete were classified into the raw material production stage, the material transportation stage, and the concrete production stage. After quantifying the energy and CO_2 that were consumed and emitted in each stage, their effect on the environment was comprehensively reviewed. Based on these results, measures to improve the environmental conditions were determined, and an objective and proactive assessment method for the environmental effects was proposed. The flow of the concrete life-cycle process starting from the order of ready-mixed concrete by a construction contractor to its receipt at the construction site is shown in Fig. 1. The range of the concrete assessment scheme was determined based on the mechanisms that affect the characteristics of construction-site environments in Korea [11,12].

3.2. Classification of the assessment methods

The methods for assessing the CO_2 emission by stage according to concrete production can be described as follows.

3.2.1. Raw material production phase

For the raw material production phase, the energy consumption and CO_2 emission associated with the production of materials required for concrete production (cement, aggregate, and admixture) are computed based on the CO_2 basic unit of each material. The computation is based on the accumulation of products contained in the amount (kg) of each material involved in the production of 1 m^3 of concrete and the basic unit. Based on the resulting CO_2 emission per unit volume of concrete, the amount of CO_2 emitted from the total output of a ready-mix concrete producer was computed. For the amounts of CO_2 emitted by each material during the raw material production stage, the National LCI database of Korea and the database provided by the Japan Society of Civil Engineering were used as references; Inter-industry Analysis was employed as a reference for the computations.

The sum of the CO_2 emissions by a material per 1 m^3 of concrete and the CO_2 emissions for the total concrete output during the

Table 1
Computation of CO_2 basic units from concrete raw materials.

Material	Unit	Cost [W]	CO_2 [kg]	Reference
Ordinary Portland cement (OPC)	kg	100	0.9310	S. Korea LCI DB
Water	kg	10	0.1960	
Gravel (coarse aggregate)	kg	40	0.0040	Inter-industry analysis
Sand (fine aggregate)	kg	40	0.0013	
Fly ash	kg	42	0.0196	Japan Society of Civil Engineering
Blast furnace slag	kg	52	0.0265	
Air entraining and water reducing agent (chemical admixture)	kg	79	0.2500	

material phase can be expressed by Formulas (1) and (2), respectively.

$$E_M = \sum (M_{(i)} \times \text{basic unit}_{M,E}) \tag{1}$$

$$CO_{2M} = \sum (M_{(i)} \times \text{basic unit}_{M,CO_2}) \tag{2}$$

(i = 1: cement, 2: coarse aggregate, 3: fine aggregate, 4: admixture, 5: water).

Here, E_M is the energy consumption for the production of a unit of concrete during the material phase [MJ/m^3], CO_{2M} is the amount of CO_2 emitted from the production of a unit of concrete during the material phase [kg-CO_2/m^3], $M_{(i)}$ is the amount of each material used per 1 m^3 of concrete [kg], basic unit$_{M,E}$ is the basic unit of energy for each material [MJ/kg], and basic unit$_{M,CO_2}$ is the basic unit of CO_2 for each material [kg-CO_2/kg] (Table 1) [13,14].

3.2.2. Raw material transportation phase

For the raw material transportation phase, the amount of oil consumed by the freight vehicle for transporting raw concrete materials from the material producer to the concrete producer was computed. In this computation, the transportation distance for each material, the type and standard fuel efficiency of the freight vehicle and the load of the freight vehicle were examined. The common practices of Korean contractors who use ready-mix concrete were also investigated. The amount of CO_2 emitted was calculated based on the average distance between the producers of each material and the concrete producer (30 km), the capacity of the freight vehicles (15 tons), and the standard fuel efficiency (2.6 km).

$$CO_{2T} = \sum \left\{ \left(\frac{M_{(i)}}{L_t} \right) \times \left(\frac{d}{e} \right) \times \text{basic unit}_{T,CO_2} \right\} \tag{3}$$

$$COST_T = \sum \left\{ \left(\frac{M_{(i)}}{L_t} \right) \times \left(\frac{d}{e} \right) \times \text{unit cost}_{T,COST} \right\} \tag{4}$$

(i = 1: cement, 2: coarse aggregate, 3: fine aggregate, 4: admixture).

Here, CO_{2T} is the amount of CO_2 emitted due to the production of a unit of concrete during the transportation phase [kg-CO_2/m^3], $COST_T$ is the economic feasibility of the production of a unit of concrete during the transportation phase [won/m^3], $M_{(i)}$ is the amount of each material per 1 m^3 of concrete [ton], $L_{t(i)}$ is the loading for the transportation of each material [ton], d is the transportation distance [km], e is the mileage [km/L], basic unit$_{T,CO_2}$ is the basic unit of CO_2 emissions for the source of energy used during transportation [kg-CO_2/L], and unit cost$_{T,COST}$ is the unit cost of the source of energy for transportation [won/L].

3.2.3. Concrete production phase

A standard energy computation method, which was established based on the current process flow of the ready-mix concrete producer and the capacity data from each facility, was utilized to assess the CO_2 emission during the concrete production stage. The standard energy computation method uses the daily energy consumption of the batcher plant, which comprises a silo, measuring devices, mixers and other items, as well as the ready-mix concrete production output data to compute the CO_2 emission based on the power consumption of each production facility involved in producing 1 m^3 of concrete. To obtain the amount of power used by each production facility while producing 1 m^3 of concrete, the production process is first classified into storage, transportation, measurement, and mixing. The amount of work associated with each facility is obtained by analyzing the ratio of the capacity of the classified facilities to the daily power use. Using the calculated CO_2 emission per unit volume, the CO_2 emission for the total energy employed to produce concrete is computed.

$$E_F = \sum \left(\frac{E_y}{R + E_{(i)}} \right) \times \text{basic unit}_{E,E} \tag{5}$$

$$CO_{2F} = \sum \left\{ \left[\left(\frac{E_y}{R} \right) + E(i) \right] \times \text{basic unit}_{E,CO_2} \right\} \tag{6}$$

(i = 1: storage equipment, 2: transportation equipment, 3: mixing equipment, 4: other equipment).

Here, E_F is the energy consumption of a unit of concrete in the production phase [MJ/m^3], CO_{2F} is the amount of CO_2 emitted per unit of concrete in the production phase [kg-CO_2/m^3], E_y is the yearly kerosene consumption [ℓ], R is the yearly ready-mixed concrete output [m^3], $E_{(i)}$ is the consumption of electricity by manufacturing equipment during each process [kwh], basic unit$_{E,E}$ is the basic unit of energy consumption for each energy source [MJ/unit], basic unit$_{E,CO_2}$ is the basic unit of CO_2 emissions for each energy source [kg-CO_2/unit], and y denotes kerosene (Table 2) [15,16].

4. Concrete life-cycle CO_2 emission assessment

4.1. Overview

The assessed concrete was a composite of common Portland cement, blast furnace slag ground, fly ash, coarse aggregate, fine aggregate, water, and a water-reducing admixture with various proportions and compressive strengths of 18, 21, 24, 27, 30, and 35 MPa. Such components are used by 10 ready-mix concrete producers in Korea. Data for approximately 560 different mix proportions were classified by strength, admixture type, and season (standard/winter).

Table 2
Concrete CO_2 emission assessment database establishment.

Construction stage	Database classification
Material production stage	Concrete mix design CO_2 basic unit by material
Material transportation stage	Transportation distance by material Load of transportation vehicle by material Fuel efficiency of transportation vehicle by material
Concrete production stage	Material mixing/grinding process Material measuring/mixing Completion process

Table 3
Concrete strength of concrete mix designs.

Strength [MPa]	Mix amount [kg/m^3]						
	G	S	C	FA	BS	W	AD
18	885	925	216	41	35	180	2.04
	864	621	271	37	0	169	2.16
21	895	866	172	34	138	175	2.06
	935	873	287	32	0	169	1.6
24	910	818	188	38	151	172	2.26
	937	845	304	45	0	174	2.09
27	894	790	210	42	168	179	2.52
	927	829	328	49	0	175	2.64
30	895	878	287	38	57	157	3.06
	921	788	348	61	0	178	3.07
35	910	769	335	54	58	176	3.13
	915	818	385	30	0	167	3.91

4.2. Assessment target and method

The mix table from the construction site was classified based on compressive strength, season, and admixture, and then evaluated. The amount of emitted CO_2 increased as the compressive strength of the concrete increased from 18 MPa to 35 MPa. This increase was analyzed using graphs and equations so as to investigate the relationship between the compressive strength and CO_2 emission.

For the assessment by season, the life-cycle CO_2 emission of concrete with strengths ranging from 18 MPa to 35 MPa was classified based on whether the life cycle was observed during a standard season or the winter season. The relationship between the season and life-cycle CO_2 emission was subsequently investigated. For the admixture assessment, the relationship between the CO_2 emission, which increases or decreases according to changes in the content, and the compressive strength of the concrete admixture is analyzed. A standard mix used in this study is shown in Table 3 [17,18].

4.3. Assessment results

4.3.1. Concrete $LCCO_2$ assessment by compressive strength (admixture replacement ratio less than 10%)

The life-cycle CO_2 emission from concrete as its compressive strength increases from 18 MPa to 35 MPa was analyzed. This assessment was limited to mix data for an admixture rate of less than 10%. The CO_2 emission increases as the compressive strength increases; this trend is shown in Fig. 2.

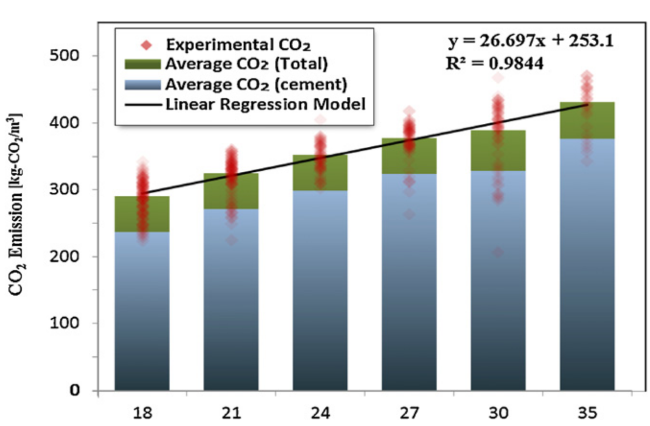

Fig. 2. Average amount of CO_2 emitted as a function of the concrete compressive strength.

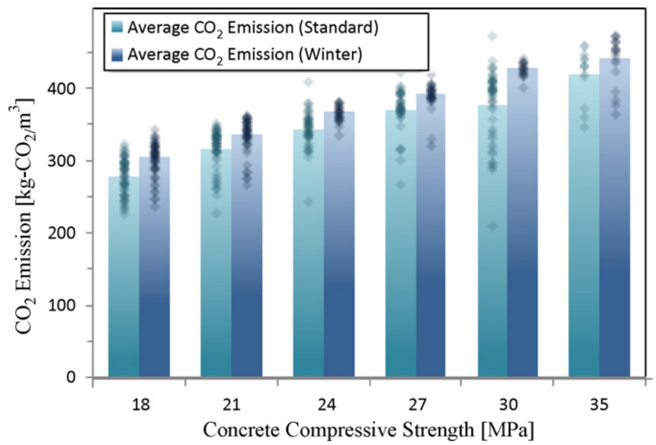

Fig. 3. Average amount of CO_2 emitted by strength and season.

As the strength increased by one level, the CO_2 emission increased linearly. This trend is similar to that observed for the rate of increase in the amount of cement material. Thus, it can be concluded that the compressive strength of concrete, the amount of cement, and the CO_2 emission are closely related to one another. As the compressive strength of concrete increased, the CO_2 emission jumped from 302.85 [kg-CO_2/m^3] at 18 MPa to 448.75 [kg-CO_2/m^3] at 35 MPa. Based on this result, a formula relating the changes in the CO_2 emission to an increase in the compressive strength of concrete was developed.

$$Y_{CO_2} = 26.697 \times \mathrm{MPa} + 253.1 \tag{7}$$

The above formula, which was obtained using regression analysis, has a high R^2 of 0.9844. Thus, the formula can be used to assess the CO_2 emission of concrete with a strength less than 18 MPa or greater than 35 MPa.

4.3.2. Concrete $LCCO_2$ assessment by season

The mix designs of concrete were classified into standard seasons and the winter season depending on when the concrete was produced. The CO_2 emission depending on the season was then analyzed. A difference in the CO_2 emissions between a standard season and the winter season is clearly visible in Fig. 3. The CO_2 emission increases as the strength increases, and the difference between the standard season and the winter season is almost constant across the strengths. In other words, as the compressive strength of concrete increases from 18 MPa to 35 MPa, the difference in CO_2 emission is approximately constant (4–6%) between the standard season and the winter season. This difference is approximately constant because the amount of admixture was reduced and the amount of cement was increased in the mix design during the winter, as curing is more difficult during the winter season.

4.3.3. Concrete $LCCO_2$ assessment by admixture

To analyze the rate of increase or decrease in CO_2 emission depending on changes in the amount and type of admixtures in the concrete, an assessment was conducted with varying constraints.

4.3.3.1. Concrete $LCCO_2$ assessment by admixture type. To analyze the changes in the CO_2 emission of concrete depending on the type of admixture used in the concrete, mix designs with an identical compressive strength of 24 MPa were classified based on the type of admixture, and their CO_2 emissions were subsequently analyzed. These results were also compared with the CO_2 emission of the standard concrete mix design at 24 MPa, which is provided by the national LCI database.

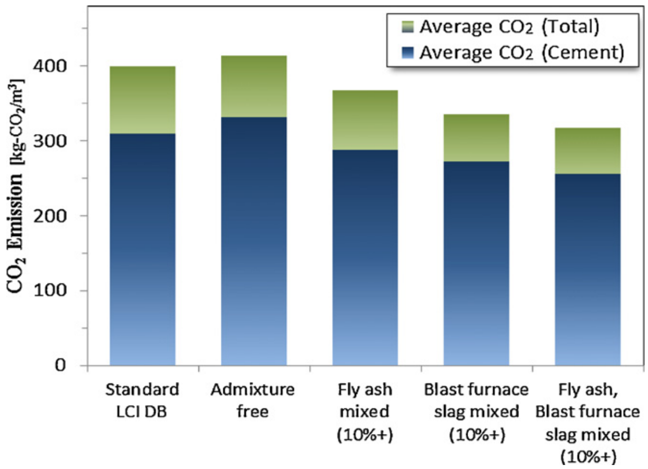

Fig. 4. Amount of CO_2 emitted from concrete depending on the type of admixture.

The concrete with both fly ash and blast furnace slag had the lowest CO_2 emission; the CO_2 emission was reduced by about 47% when compared to the CO_2 emission of the concrete with no admixture. The amount of CO_2 emitted from the concrete provided by the national LCI DB shows a 20% increase when compared to the CO_2 emission of the concrete with no mix. Thus, the concrete from the national LCI database includes about 20% admixture. The actual mix proportion of admixture in the concrete of the national LCI DB is 15%, which is very close to the estimate. In addition, when only fly ash is added, the CO_2 emission was reduced by 27% when compared to the CO_2 emission for the mix with only blast furnace slag. Such a difference is due to the different CO_2 basic unit of each material (Fig. 4).

4.3.3.2. Concrete LCCO$_2$ assessment by admixture replacement ratio. To investigate the relationship between the CO_2 emission of concrete and the mix proportion of admixture used in the concrete, mix designs were classified based on compressive strength, and the CO_2 emission was assessed depending on different mix proportions of blast furnace slag and fly ash.

The CO_2 emission of concrete with respect to the amount of admixture is shown in Fig. 5. The overall CO_2 emission tends to decrease with the addition of fly ash and blast furnace slag Furthermore, 88% of all mix designs had an admixture-cement ratio of less than 20%, which indicates that concrete with a higher amount of admixture is rarely used. At a strength of 30 MPa, the assessment results show a difference as large as 152.7 [kg-CO_2/m^3] when admixtures are added, which is a 36% reduction from the maximum CO_2 emission. The most relevant aspect of this difference is that the CO_2 emission is reduced not because of the addition of a special admixture, but because the amount of cement decreased.

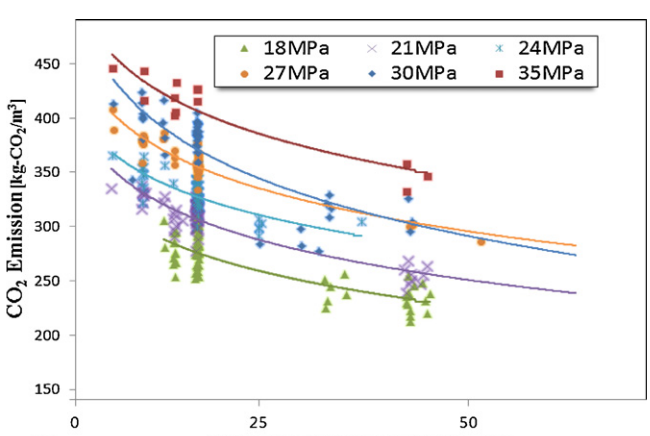

Fig. 5. CO_2 emission of concrete upon the addition of admixtures.

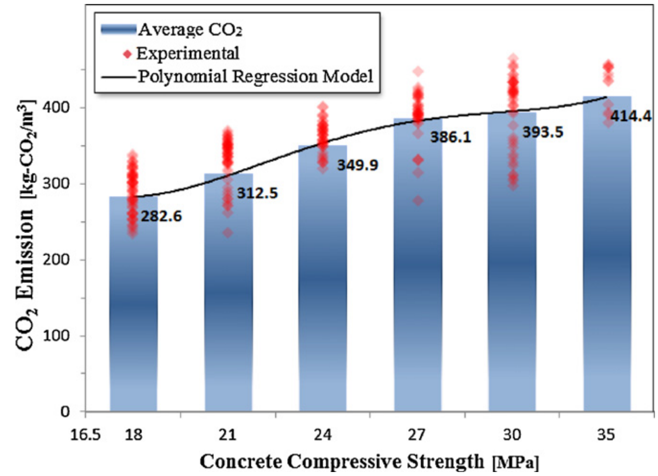

Fig. 6. Amount of CO_2 emitted from concrete with admixture as a function of the compressive strength.

4.3.3.3. Concrete LCCO$_2$ assessment by compressive strength (admixture replacement ratio greater than 10%). The life-cycle CO_2 emission of concrete with more than 10% each of fly ash and blast furnace slag among concretes with compressive strengths ranging from 18 MPa to 35 MPa was analyzed.

Fig. 6 shows that the CO_2 emission increases irregularly when compared to the emission from concrete with no admixture. Although the required amount of cement increases as the compressive strength of the concrete increases, the mix proportion of admixture also increases, which changes the proportion of cement. For a clearer view of the relationship between the admixture and CO_2 emission, the CO_2 emission of concrete with no admixture and that of concrete with over 30% of admixture are compared in Fig. 7.

It was confirmed that the CO_2 emission was reduced for all mix proportions of admixtures regardless of the compressive strength of the concrete. In addition, CO_2 emission reductions of 51.5 kg-CO_2 and 77.6 kg-CO_2 were observed for concretes with compressive strengths of 18 MPa and 35 MPa, respectively, due to the addition of admixtures. Such a result indicates that the reduction in CO_2

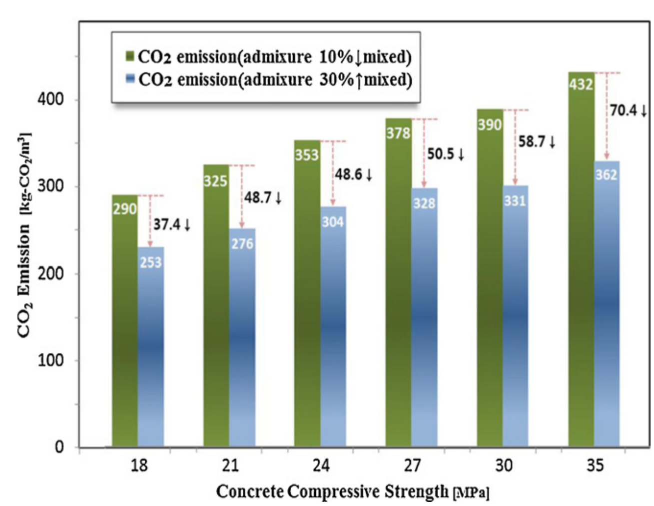

Fig. 7. Amount of CO_2 emitted from concrete according to the mixing of admixtures and the compressive strength.

emission from concretes with admixtures is greater when the compressive strength of the concrete is larger. Thus, the development of high strength concrete coupled with an analysis of the effects of admixtures will effectively reduce CO_2 emissions.

5. Conclusion

To establish an environmentally friendly concrete production assessment system, the life-cycle CO_2 emission was evaluated based on the compressive strength (by admixture and season) of concrete, and the relationship among the examined parameters was investigated. The following conclusions can be drawn from the obtained results:

1. The life-cycle CO_2 emission from concrete increased linearly as the compressive strength of the concrete increased; the life-cycle CO_2 emission was about 48% larger at 35 MPa than at 21 MPa.
2. At identical compressive strengths, the concrete produced in the winter showed an approximately 5% increase in CO_2 emissions when compared to concrete produced in a standard season.
3. The amount of CO_2 emitted by concrete with admixtures was lower by as much as 47% (a significant reduction) when compared to that of concrete with no admixture. This result appears to be due to the replacement of cement, which has a high CO_2 basic unit, with admixtures such as blast furnace slag or fly ash, which have low CO_2 basic units.
4. Mixing over 10% each of fly ash and blast furnace slag into concrete with compressive strengths of 35 MPa and 18 MPa reduced the life-cycle CO_2 emission by 77.6 kg-CO_2 and 51.5 kg-CO_2, respectively.
5. A regression analysis was performed based on the strength, season, and admixture of concrete so as to assess CO_2 emissions during the life cycle of a building. From the regression analysis, a regression equation with a high coefficient of determination was obtained. Such an equation allows the CO_2 emissions from concrete with different strengths to be measured under the same conditions.

Acknowledgement

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